REPORT DOCUMENTATION PAGE

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
19/05/2009	Final Report	15/07/06 – 14/01/09

4. TITLE AND SUBTITLE

Diagnostics for wind tunnel dynamic flight maneuvering using controlled, trapped vorticity

5a. CONTRACT NUMBER

5b. GRANT NUMBER

FA9550-06-1-0486

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Ari Glezer

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Ari Glezer
Woodruff School of Mechanical Engineering
Georgia Institute of Technology

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR
875 N Randolph St
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-OSR-VA-TR-2012-0463

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This equipment will be used for detailed, time resolved flow field diagnostics in a number of AFOSR sponsored an other DOD sponsored investigations of active aerodynamic flow control. The near term use of this equipment will concentrate on two degrees of freedom dynamic maneuvering of a wing model in wind tunnel testing to support the experimental effort of a five year AFOSR MURI Program that began in July 2005 and includes the Georgia Institute of Technology, the University of Illinois, the University of Texas, Austin and the California Institute of Technology.

15. SUBJECT TERMS

equipment, aerodynamic, flow, diagnostics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Douglas Smith
					19b. TELEPHONE NUMBER *(Include area code)*
					703-696-6219

DIAGNOSTICS FOR WIND TUNNEL DYNAMIC FLIGHT MANEUVERING USING CONTROLLED, TRAPPED VORTICITY

Ari Glezer
Woodruff School of Mechanical Engineering
Georgia Institute of Technology

I. Overview

A high frame-rate, particle image velocimetry (PIV) system was acquired under support from AFOSR DURIP Grant FA9550-06-1-0486. The system was ordered in June 2007 and in January 2008 was installed in the Fluid Mechanics research Laboratory (FMRL) of the Woodruff School of Mechanical Engineering at the Georgia Institute of Technology. This equipment will be used for detailed, time-resolved flow-field diagnostics in a number of AFOSR-sponsored and other DoD-sponsored investigations of active aerodynamic flow control. The near-term use of this equipment will concentrate on two-degrees-of freedom dynamic maneuvering of a wing model in wind tunnel testing to support the experimental effort of a five-year AFOSR MURI Program (FA9550-05-1-0411) that began in July 2005 and includes the Georgia Institute of Technology, the University of Illinois, the University of Texas, Austin and the California Institute of Technology.

The MURI Program focuses on closed-loop flow control to achieve dynamic maneuvering and attitude control for small scale UAVs. Adaptive, closed-loop feedback control architectures will be designed based on a low-order model of the vorticity dynamics. Flow-field data is provided from surface-mounted pressure sensors (that will be augmented with and micro-fabricated tufts), and the required net forces and moments are supplied by sparse arrays of independent hybrid fluidic actuators managing the generation, accumulation (trapping), and regulation of spanwise and streamwise vorticity concentrations on the lifting surfaces. High-order detached eddy simulations will address questions of actuator and sensor placement, assess the accuracy of low - order models, and serve as a computational testbed for controller development.

The unsteady fluid dynamics (flow state) is affected by *both* the dynamic motion of the lifting surface *and* the controlled fluidic actuation, and are investigated experimentally in wind tunnel tests using a *moving* model mounted on new, two-degrees-of-freedom traversing mechanisms. While existing conventional (10 fps) PIV hardware can capture temporally-sparse phase-locked images, the new, high-speed PIV system is able to capture the instantaneous time-dependent evolution of the velocity field under close-loop control of both the flow and the vehicle dynamics.

II. The DURIP High-Speed PIV System

The High-Speed PIV system that was acquired under the current DURIP Grant is comprised of three primary components: *i.* a high-speed CCD camera and related control hardware, *ii.* a high-frequency YAG laser, and *iii.* appropriate PIV software. The equipment is currently being integrated with an existing, open-return wind tunnel and a 2-DOF traversing mechanism for detailed, time-resolved measurements of the coupling between the dynamic motion of the model's lifting surface and the controlled fluidic actuation.

I.	High-Speed PIV CCD Camera System
I.1	**High-Speed CCD Camera LaVision Model 110HS31 HighSpeedStar 3** CMOS 1024 x 1024 pixel resolution sensor, 17 x 17 micron pixels, 1000 frames/sec at full resolution, up to 109,500 frames/sec at reduced resolution, 10-bits dynamic range, 8 GB on-board memory, PCI bus interface, 5 m camera cable.
I.2	**Programmable Timing Unit (PTU) for High-Speed CCD Camera, LaVision Model 1108063:** Internal - 16 output channels, 3 input channels (trig in, image capture start/stop), 10 ns time resolution, internal for PCI bus. Additional on-board Programmable Input/Output (PIO) gives 16 program.
II.	**High-Speed Diode Pumped Nd:YLF Laser.**
II.1	**High Repetition Rate Dual Cavity Solid State Laser Quantronix Model Darwin Duo-527-80-M** Energy 22.5mJ/head total energy. Repetition Rate single shot to 10kHz, control synchronized or independent external trigger for each laser oscillator, external and internal triggering, flexible time delay and energy adjustment, built-in beam combining optics, two laser outputs synchronized to double the pulse energy, peak power, or pulse repetition rate.
III	**PIV Software**
III.1	**High-Speed Image Capture Software Package, LaVision Model 1105081:** Acquisition controls for CCD camera, includes control over frame rate, image exposure,sequence length, storage mode, etc.
III.2	**DaVis Software package (USB port dongle), LaVision Model 1108063** Version 7.x, 32- bit software for image acquisition and processing, control of all hardware components, macro programming language, included complete list of image filters, background subtraction, data import/expo
III.4	**2D PIV/PTV Software package** - cross- and auto-correlation image processing algorithms with high spatial resolution, second-order correlation, deformed window correlation, multi-pass correlation , PTV algorithms, advanced image acquisition techniques for high image thru-put and long sequence captures, vector post-processing, and image/vector display.

III.5	**System Computer.**

The DURIP funding ($192,355) was used for the purchase and subsequent installation of the complete system in the wind tunnel laboratory of the Woodruff School of Mechanical Engineering at Georgia Tech. The DURIP equipment was integrated with the optical diagnostics infrastructure in the wind tunnel laboratory by leveraging existing optical components (lenses, mirrors, mounts/carriers, etc.) and extensive software and hardware for rapid management and processing of large amounts of PIV data.

III. Technical Background

The diagnostic equipment that was acquired under the present DURIP Grant is in support of wind tunnel experiments under an AFOSR MURI Program (FA9550-05-1-0411). A team of researchers from the Georgia Institute of Technology, University of Illinois, University of texas, Austin, and the California Institute of Technology have collaborated on closed loop flow control to achieve rapid, dynamic maneuvering for small scale UAVs (Figure III.1). The problem is motivated by the pressing need to operate such vehicles in

Figure III.1. Notional Dragon Eye UAV (~1m wingspan) with closed loop flow control system.

confined areas like urban environments. Here, both rapid maneuvering and gust rejection are essential. Closed loop flow control offers a unique opportunity to achieve both. The net forces and moments required for dynamic maneuvering and attitude control can be varied independently by dynamically tailoring the surface pressure distribution on lifting surfaces using a sparse array of hybrid fluidic actuators to manage the generation and accumulation (trapping) of vorticity on and near the lifting surface.
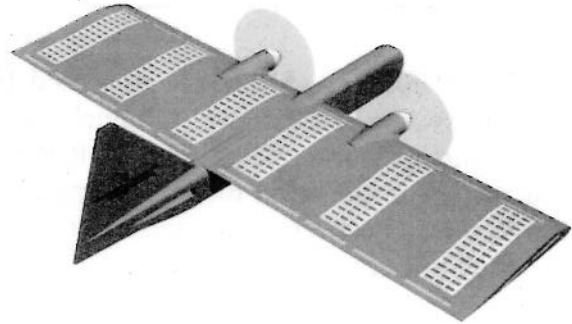
Adaptive control architectures that will control the vehicle motion use closed loop feedback from surface mounted flow sensors, as depicted notionally in Figure III.1. These pressure and flow direction sensors enable rapid, distributed sensing of flow conditions near the lifting surface. The adaptive controller design is based on a low order model of the vorticity dynamics, and it will compensate for unmodelled dynamics. In the adaptive control architecture (Figure III.2), the flow control

Figure III.2 Integrated adaptive control architecture

actuator characteristics are intimately coupled with the flow state, and cannot be viewed as simply in series with the process under control. This requires a fully integrated vehicle/flow control design. A reduced-order reference model approximately representing the vehicle dynamics interacting with flow dynamics is required that will model the influence of the nominal controller on regulated output variables ($y(t)$ consists of sensed aircraft states *and* the sensed flow variables). A reduced-order model is used to design the nominal controller, so that the nominal controller together with the reference model defines the desired closed-loop performance. The model is also used to define the error state needed for the adaptive process. It defines the expected influence of input from the nominal flight controller on the regulated vehicle variables (y), which are a subset of sensed aircraft states. The vehicle model is also used to design the nominal flight controller, so that an ideal system comprised of the nominal controller and the reference model defines the desired closed-loop performance. In reality, the controller inputs consist of the true sensed *aircraft and flow states*, and the goal of the adaptive controller is to maintain $e(t) = y(t) - y_m(t)$ as close to zero as possible.
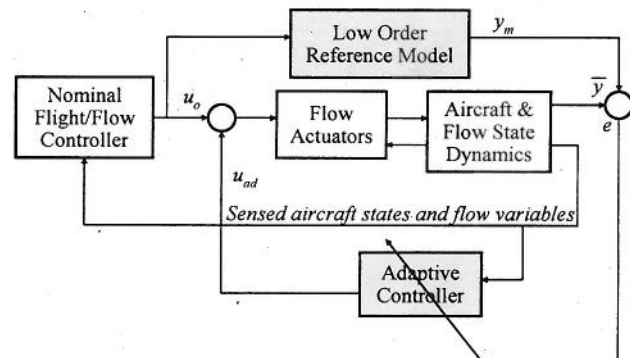
A key element of the MURI research is the development of flow control methodologies to generate the desired time-dependent aerodynamic forces and moments by manipulation and control of trapped vorticity concentrations. *The experimental flow physics research will include testing and demonstration of integrated controllers using a 1-m finite-span 2-DOF moving wing, and will include both 2-D and 3-D flow effects. (as shown schematically in Figure III.3). The model will actually "fly" (pitch and plunge) in the wind tunnel under closed-loop flow control using a novel traversing mechanism that will be developed specifically for the MURI Program.* This is a unique element of the MURI program

Figure III.3 *Wing model mounted on dynamic traverse in the tunnel test section. The main components of the proposed DURIP PIV system are shown schematically: the CCD camera (A) and the diode pumped Nd:YLF laser (B).*

since the *dynamic* maneuvers occur on sufficiently small time scales that the resulting unsteady fluid dynamics (flow state) is affected by the dynamic motion of the lifting surface as well as by controlled fluidic actuation and therefore the vehicle dynamics and fluid dynamics are intimately coupled. The wind tunnel experiments address these issues and integrate sensors and actuators with adaptive controllers, providing a testbed for controller design, in addition to providing baseline flowfield information for both CFD validation and assessment of the real-time-computable, reduced-order models suitable for direct inclusion in the plant models. High-fidelity detached eddy simulations are used for sensor/actuator placement studies and controller development. The MURI research will culminates in a flight demonstration using a 1-m scale UAV, to demonstrate the realizability of the team's results.

The high-speed particle image velocimetry (PIV) system that were purchased under the DURIP Grant will be used for detailed, time-resolved measurements of the controlled flow field about the dynamically moving airfoil in the wind tunnel experiments. Specifically, this system will enable for the first time the identification and characterization of the mechanisms by which trapped vorticity concentrations induced by hybrid actuators alter the global circulation and aerodynamic forces. It is anticipated that in some of the experiments the CCD camera will be mounted *directly* on the moving traverse and therefore will enable measurements of the flow field in the moving frame of reference of the wind tunnel model in both open and closed loop control. As noted in Section II, this equipment has already been integrated into the diagnostics infrastructure of wind tunnel laboratory by leveraging existing optical components and an extensive suite of software and hardware that
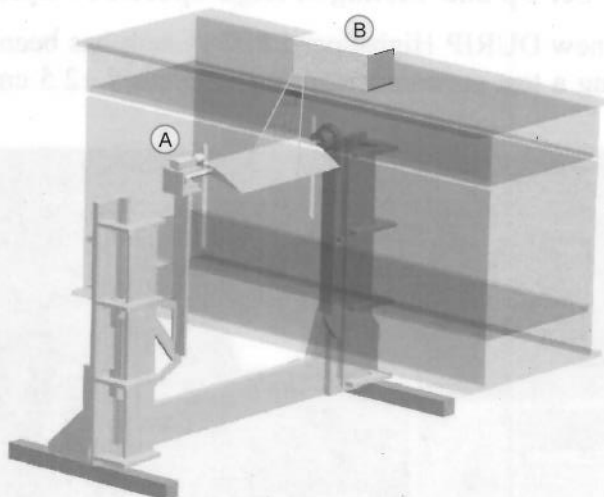
IV. Set Up and Testing of High-Speed PIV System

The new DURIP High-Speed PIV system has been tested in a small-scale transonic wind tunnel having a test section measuring 12.5 cm x 12.5 cm in the cross-stream plane. The open-return
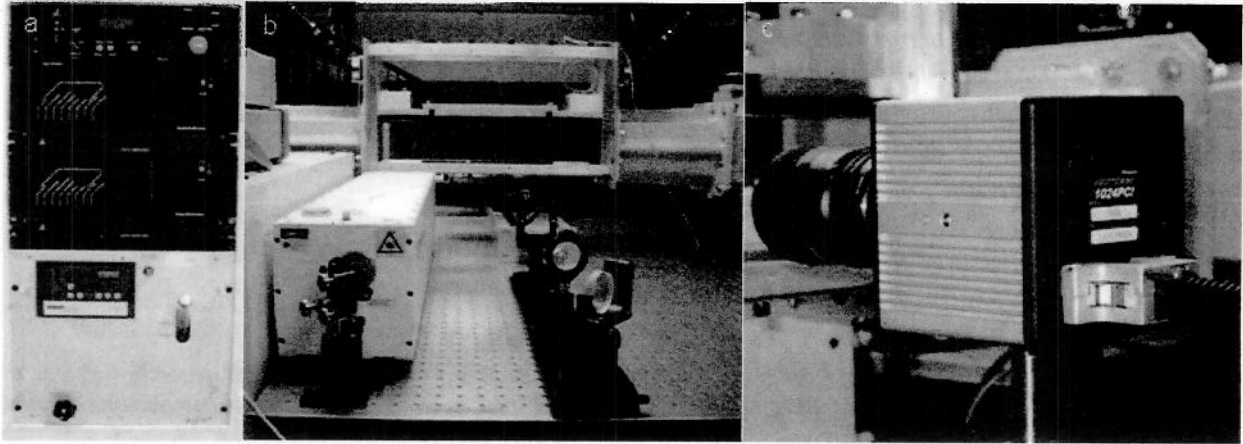

Figure IV.1 *The new High-Speed PIV system: (a) The 10 KhZ laser power supply, (b) The optical table showing the laser head and the transmitting optics next to the transonic tunnel, and (c) the CCD imager.*

tunnel is operated in suction mode through a high-ratio (200:1) contraction where the PIV seeding is injected into the flow. Figure IV.1 shows the optical setup next to the tunnel's test section. The high-speed diode pumped Nd:YLF Laser is shown in Figures IV.1a (the power supply) and b (the laser head). As noted in Section II, the dual-cavity Quantronix laser is capable of providing up to 22.5 mJ/head at variable repetition rates of up to 10kHz. Figure IV.1b also shows the optical table and transmitting optics next to the tunnel's test section. The laser sheet (in the cross stream plane $z = 0$) enters the test section through the bottom wall and the PIV camera is placed on the other side of the test section (Figure IV.1c). The calibration data was obtained using high-resolution PIV images within the wall boundary layer of the tunnel ($\delta = 6$ mm) and the free stream speed is nominally 160 m/sec. Figure IV.2 shows time-averaged cross stream velocity distributions and spanwise vorticity concentrations of the flow over a micro-ramp within the boundary layer (the cross stream height of the ramp is about 2.5 mm). These data show flow separation at the downstream edge of the ramp and its near wake and small recirculation domain. Other PIV measurements (not shown) demonstrated the formation of streamwise vortices downstream of the ramp. For these data, the PIV system was operated at full speed (500 frame pairs per sec). The high-speed PIV system is now fully operational and ready for data acquisition in the MURI flow control experiments.
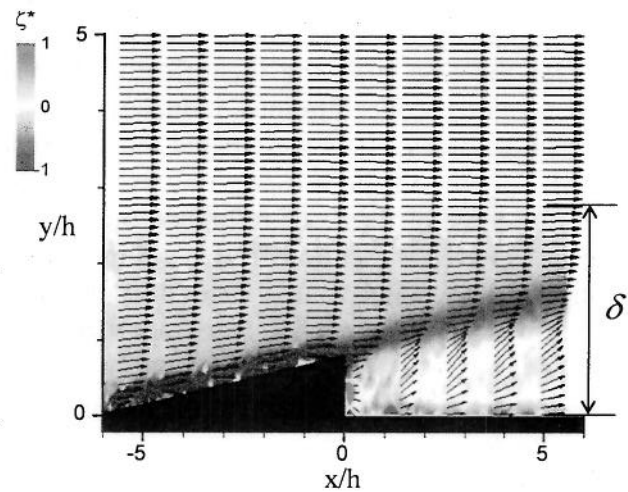

Figure IV.2 *PIV image of boundary layer flow over a 2.5 mm micro ramp obtained at 500 pf/sec.*